

Measurement of kinetic energy dissipation with gelatine fissure formation with special reference to gelatine validation

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Abstract

Various methods for calculating the amount of kinetic energy dissipated by a bullet into ballistic gelatine have been suggested in literature. These methods were compared using the results of thirteen 9 mm × 19 mm pistol and five 7.62 mm × 39 mm rifle bullets shot into 10% ballistic gelatine.

The Wound Profile Method gave the highest correlation, 0.89, with the measured amounts of dissipated kinetic energy. The Fissure surface area and total crack length method gained 0.51 and 0.52, respectively.

The experimental results were also compared with those from pig tests with the same bullet types. Using the *z*-test at 95% level of confidence no difference between impact velocity normalized bullet decelerations could be determined for the 9 mm bullet used. The same test showed significant difference for 7.62 mm bullets. That, however, can be considered to be the result of the bullet's tendency to tumble in non-homogenous living tissue causing significant dispersion of observed deceleration values. The results add further evidence supporting the validity of 10% gelatine at +4 °C as wound ballistic tissue simulant.

The study also introduces the use of an elastic “shroud” to hold the gelatine in place, to some extent reduce the effects of asymmetric expansion of the gelatine and to simulate the expansion suppression effect of surrounding tissues.

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1. Introduction

When a projectile penetrates a block of gelatine the pressure causes the bullet channel to rapidly expand and to create a temporary cavity which collapses in pulsations when the pressure subsides. The expansion and probably also subsequent pulsations break the structure of gelatine leaving in it a channel like the one shown in Figs. 1 and 2. It is a generally accepted fact that the fissures thus formed reflect the distribution of kinetic energy E_d dissipated by the

projectile into the simulant. There are a number of methods used for calculating this energy. This study looks into three of them and attempts to establish their fidelity. The absolute amount of dissipated kinetic energy E_d is

$$E_d = E_i - E_{\text{def}} - E_r \quad (1)$$

where E_i is impact energy, E_{def} the energy used for bullet deformation and E_r the residual energy of the bullet exiting the target. The fissure measurement can be used for estimating the proportion of energy E_{di} transferred into any section i of the bullet channel. Once E_{di} is known, an estimate of tissue destruction or devitalisation can be made to assess the

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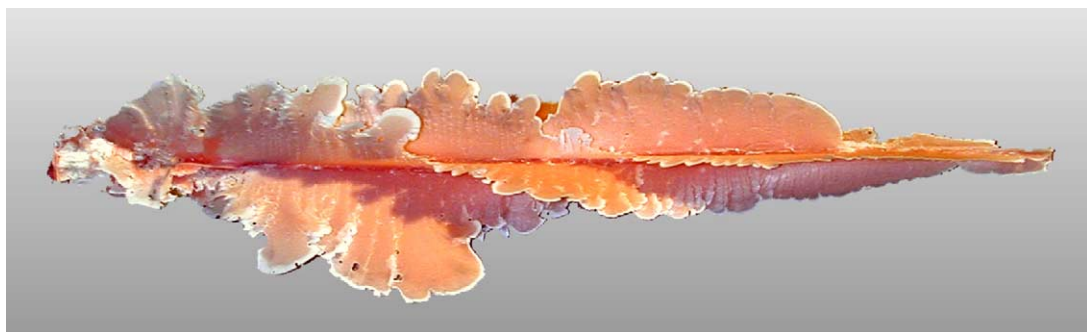


Fig. 1. Bullet channel formed in gelatine can be cast using two component plastic and preserved. The fissures seem to reflect the rotation of the bullet. The channel was formed by a 9 mm × 19 mm Speer Gold Dot hollow point bullet.

bullet's injurious potential since tissue destruction correlates with dissipated energy [1,2,3,4,10].

In all measurement methods the gelatine is cut into sections usually 50 mm thick. An example of a gelatine section is shown in Fig. 3. Each method can be used for calculating an energy ratio figure, RE, which is the sum of all RE_i's calculated for each section *i*.

The Fissure surface area (FSA) method by Knappworst ([1], pp. 192–194) suggests that

$$\sum r_i = c(E'_{tr})^i \quad (2)$$

where $\sum r_i$ represents the sum of all crack lengths at a certain cross-section of the gelatine block. *c* is a constant and E'_{tr} is the kinetic energy the projectile dissipated into the section *i* of the block. Thus, the sum of all lengths of all cracks in section *i* is claimed to be proportional to the energy dissipated into that section.



Fig. 2. Cross-section of a 7.62 mm × 39 mm bullet channel formed in gelatine.

For a bullet channel of length l_w the energy ratio number RE_{FSA} can thus be estimated as

$$RE_{FSA} = SRE_i \quad (3)$$

where RE_{*i*} is the ratio number for a section *i* and

$$RE_i = \sum r1_i l_w + \frac{1}{2} |\sum r1_i - \sum r2_i| l_w \quad (4)$$

where $r1$ and $r2$ are the $\sum r$ for impact and exit sides of the section, respectively.

The total crack length method (TCLM) [5] estimates temporary cavity size from the fissures assuming that the fissures have been formed as sections of the circumference of the maximum expansion, i.e. temporary cavity of the bullet channel. Therefore, the radius of the temporary cavity is:

$$r_{tc} = \frac{\sum r}{2\pi} \quad (5)$$

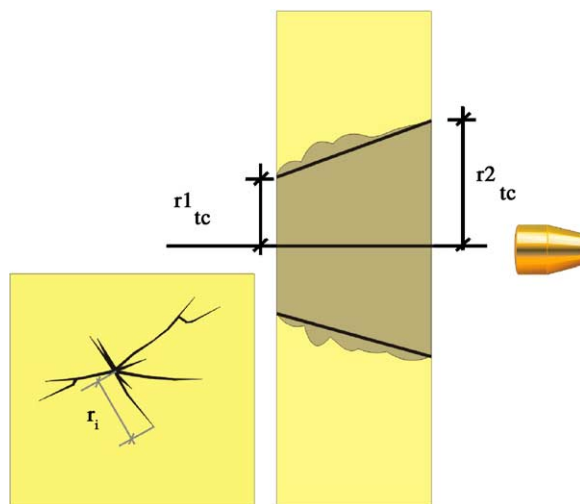


Fig. 3. Schematic of a gelatine section.

and RE_{TCLM} can be expressed as the sum (Eq. 3) of all volumes of temporary cavity of the section:

$$RE_i = \frac{1}{3}\pi l_w(r1_{tc}^2 + r1_{tc}r2_{tc} + r2_{tc}^2) \quad (6)$$

The wound profile method (WPM) [6] takes the two largest cracks and adds their lengths $r1_{max}$ and $r2_{max}$ together to produce an estimate of the temporary cavity diameter. We thus obtain:

$$r_{tc} = \frac{1}{2}r1_{max} + r2_{max} \quad (7)$$

and the RE_{WPM} as in Eq. (6) above.

The purpose of this study was to find out the correlations of RE with the measured kinetic energy E_d dissipated into gelatine and to establish the most reliable method of measurement to obtain the relative amounts of kinetic energy transferred into the simulant at any part of the projectile path when impact and residual energies are measured and to derive corresponding estimates for devitalised tissue.

2. Materials and methods

- 9 mm × 19 mm Norma “säkerhetspatron” ammunition with 8.0 g full metal jacketed truncated cone bullet (Fig. 5).
- SIG P226 9 mm × 19 mm pistol barrel (112 mm) mounted on a stationary general purpose action.
- 7.62 mm × 39 mm Sako ammunition with 8.0 g full metal jacketed bullet (Fig. 5).
- Sako barreled 7.62 mm × 39 mm action with 415 mm barrel.
- 20 cm × 20 cm × 25 cm gelatine blocks made to Police Technical Centre standard PTK-MO-A-0006 [7] and used at the temperature of +4 °C.
- Impact velocity chronograph Oehler 35 P with three (dual measurement) model 55 optical gates.
- Residual velocity chronograph consisting of a 100 MHz Tektronix TDS220 oscilloscope connected to dual Oehler model 57 infrared gates with 100 mm distance between measurement planes. The screens were complemented with witness papers set 180 mm apart for measurement of flight path angle.
- Broemel QuickTarget version 1.20 ballistic software.
- Microsoft Excel version 9.0.3821.

The ammunition types were selected to have two distinctly different energy classes and to have bullets that do not deform in gelatine to the extent that it would introduce error in measurements by having a significant value of E_{def} . It was also considered important to use the ammunition types that have previously been used in pig tests in order to be able to compare kinetic energy dissipations [2,8,9,10].

Both weapon types were mounted on a stationary machine rest and aimed using a collimated laser. See

Fig. 4 for testing arrangement. Gelatine penetration resistance was verified by shooting two 4.5 mm steel pellets. All penetrations conformed to the requirement of penetration function

$$l_w = 0.594v_i - 21.92 \pm 5 \quad (8)$$

where l_w is the penetration (mm) and v_i impact velocity (m/s) [7].

The impact and residual velocity chronographs were calibrated. This was done by placing the screen assembly of the latter as close to the middle screen of the impact velocity chronograph and shooting through both sets of gates simultaneously. The difference between the chronograph readings was <1 m/s and no correction was therefore deemed necessary.

A synthetic tissue simulant whether gelatine or soap presents three problems that are emphasized by the use of high energy, high velocity bullets. The first is that the simulant does not expand evenly in all radial directions as it must be supported from the bottom. Secondly, the cavitation suppressing effect of surrounding tissue is to some extent missing. Thirdly the gelatine block may fall on the floor on impact. All three can be claimed to introduce errors to the results. The two first issues have briefly been addressed in literature [11,12].

The problems can be averted if large enough simulant blocks are used. An alternative method to resolve the problems and to gain more consistent measurements was done by using “a shroud” made of elastic garment with maximum elongation of approximately 60% and a velcro strip as a fastener. The first gelatine block was placed on a platform covered with 10 mm thick foam rubber and wrapped snugly but not tightly in place with the 25 cm wide shroud. It covered the entire length of the block leaving the ends free. The shroud held the gelatine in place and allowed it to expand sufficiently for the measurement of E_d distribution. It can also be claimed to provide similar support as surrounding tissue in a human being and cause more even radial distribution of E_d .

For actual testing the weapon barrel was aligned precisely perpendicular to the impact velocity gates. This gives the true velocity reading without any need to correct the value due to flight path angle. As, however, the distance between the impact velocity middle screen measurement plane and the gelatine was 2.5 m, the measured velocity needed to be corrected with bullet deceleration to obtain the true impact velocity v_{ic} . The ballistic software gave the theoretical values of −2.5 m/s for the 7.62 × 39 and −2 m/s for the 9 × 19 that were subtracted from the measured velocities v_i .

Residual velocity measurement was assumed to require correction due to the unknown angle the projectile exits from gelatine. It is safe to assume that penetrating a block of tissue simulant affects the flight path by an unknown amount. This means that the same orientation based method as with impact velocity gates cannot be used. The actual flight path

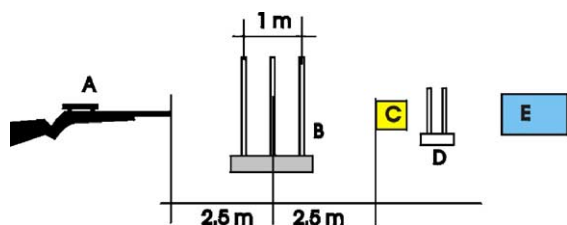


Fig. 4. Testing arrangement: (A) weapon; (B) impact velocity measurement; (C) gelatine; (D) residual velocity measurement and (E) backstop of cellulose wadding.

must be measured and the residual velocity reading corrected with the actual distance the bullet travelled between the gates.

This was done by attaching a witness paper on both sides of the gates. Once the entry coordinates relative to a chosen reference point like the left lower corner of the gate opening and the exit coordinates are known it is a simple trigonometric task to calculate the actual distance a bullet travelled between the gates. Dividing this distance with the distance between the witness papers will give us a velocity correction coefficient c_v which we use to obtain corrected velocity v_{rc} from measured residual velocity v_r .

$$v_{rc} = c_v v_r \quad (9)$$

The distance between the rear end of the gelatine block and the first residual velocity screen was 20 cm. Bullet deceleration over this distance is negligible and any velocity correction due to this distance was therefore not considered necessary.

No significant deformation was observed on the fired bullets. See Fig. 5. The energy E_d dissipated into gelatine is therefore the difference between impact energy E_i and residual energy E_r . Gelatine blocks were cut to 50 mm sections. The bullet penetration channels were measured and RE-values calculated using all three methods. The literature does not describe accurately how the lengths of the fissures should be measured and what constitutes a fissure. The method used in this study was to measure the length as the linear distance between the centre of the bullet penetration channel and the farthest end of the fissure. Pearson correlations of RE figures and measured values of E_d were calculated.

The results obtained were then used to compare the relative kinetic energy dissipations in pig tests [2,8,9] in order to obtain a picture on the fidelity of 10% gelatine as tissue simulant.

A total of 13 wound channels of the 9 mm bullet and five produced by the 7.62 mm bullet were analysed.

3. Results

The detailed results are shown in Tables 1–3. They show that the WPM gives the best and a very high correlation of 0.89 (Table 4) with the expended energy E_d . The FSA method obtained correlation coefficient of 0.51 and the TCLM 0.52.

The decelerations caused by living pig muscle and 10% gelatine were compared. As the impact velocities of pig and gelatine tests were different the decelerations were normal-



Fig. 5. Recovered 9 mm × 19 mm Norma bullet (left) and 7.62 mm × 39 mm Sako bullet. The Norma bullet shows slight indentation of the tip which was considered insignificant for the purpose of the study.

Table 1
Crack (fissure) length measurement data

Fissures for 9×19		Sums of fissure lengths (mm)					
Shot no.	Method	0	50	100	150	200	250
1	FSA	4.50	106.68	84.43	86.13	61.45	250
	TCLM	4.50	33.96	26.87	27.42	19.56	250
	WPM	4.50	16.73	22.74	18.39	17.64	250
2	FSA	4.50	99.26	58.13	55.73	70.22	250
	TCLM	4.50	31.60	18.50	17.74	22.35	250
	WPM	4.50	23.22	16.87	17.67	16.88	250
3	FSA	4.50	69.59	91.79	76.78	67.06	250
	TCLM	4.50	22.15	29.22	24.44	21.35	250
	WPM	4.50	20.85	24.68	20.33	18.73	2.50
4	FSA	4.50	84.32	87.68	76.14	78.62	2.50
	TCLM	4.50	26.84	27.91	24.24	25.03	2.50
	WPM	4.50	20.71	20.56	19.17	17.87	2.50
5	FSA	4.50	85.72	101.30	69.72	58.59	2.50
	TCLM	4.50	27.29	32.24	22.19	18.65	2.50
	WPM	4.50	18.43	21.04	17.30	16.62	2.50
6	FSA	4.50	129.04	2.50			
	TCLM	4.50	41.07	2.50			
	WPM	4.50	24.30	2.50			
7	FSA	4.50	93.13	2.50			
	TCLM	4.50	29.64	2.50			
	WPM	4.50	25.62	2.50			
8	FSA	4.50	109.33	2.50			
	TCLM	4.50	34.80	2.50			
	WPM	4.50	21.83	2.50			
9	FSA	4.50	67.48	2.50			
	TCLM	4.50	21.48	2.50			
	WPM	4.50	20.00	2.50			
14	FSA	4.00	88.48	83.14	85.10	66.40	2.50
	TCLM	4.00	28.16	26.46	27.09	21.14	2.50
	WPM	4.00	21.83	25.34	19.84	15.70	2.50
15	FSA	4.00	101.41	54.02	78.46	58.00	2.50
	TCLM	4.00	32.28	17.20	24.97	18.46	2.50
	WPM	4.00	20.12	18.46	21.13	16.80	2.50
16	FSA	4.00	75.29	62.49	66.40	69.60	2.50
	TCLM	4.00	23.97	19.89	21.14	22.15	2.50
	WPM	4.00	20.15	23.92	15.00	16.55	2.50
17	FSA	4.00	66.80	67.65	76.00	63.20	2.50
	TCLM	4.00	21.26	21.53	24.19	20.12	2.50
	WPM	4.00	18.60	22.90	20.80	17.20	2.50
Mean	FSA	4.35	90.50	53.89	74.50	65.90	2.50
	TCLM	4.35	28.81	17.68	23.71	20.98	2.50
	WPM	4.35	20.95	15.88	18.85	17.11	2.50
S.D.	FSA	0.23	17.82	36.65	8.91	6.13	0.00
	TCLM	0.23	5.67	10.93	2.84	1.95	0.00
	WPM	0.23	2.35	9.20	1.86	0.83	0.00
Fissures for 7.62×39							
11	FSA	5.00	176.29	8.35			
	TCLM	5.00	56.11	8.35			

Table 1 (Continued)

Fissures for 9 × 19		Sums of fissure lengths (mm)					
Shot no.	Method	0	50	100	150	200	250
12	WPM	5.00	29.29	8.35			
	FSA	3.80	119.07	107.49	114.16	193.49	11.57
	TCLM	3.80	37.90	34.22	36.34	61.59	11.57
	WPM	3.80	21.55	19.66	26.63	41.60	11.57
13	FSA	3.80	112.78	112.65	124.37	84.01	8.84
	TCLM	3.80	35.90	35.86	39.59	26.74	8.84
	WPM	3.80	24.79	28.87	34.37	30.05	8.84
18	FSA	3.75	96.33	144.30	127.50	134.80	7.49
	TCLM	3.75	30.66	45.93	40.58	42.91	7.49
	WPM	3.75	19.07	26.05	25.54	30.64	7.49
19	FSA	3.75	96.00	115.70	189.55	122.18	22.00
	TCLM	3.75	30.56	36.83	60.34	38.89	22.00
	WPM	3.75	21.15	28.70	44.08	36.12	22.00
Mean	FSA	4.02	120.09	97.70	138.90	133.62	12.47
	TCLM	4.02	38.23	32.24	44.21	42.53	12.47
	WPM	4.02	23.17	22.33	32.65	34.60	12.47
S.D.	FSA	0.49	29.52	46.47	29.66	39.30	5.69
	TCLM	0.49	9.40	12.62	9.44	12.51	5.69
	WPM	0.49	3.57	7.74	7.42	4.68	5.69

Note: For shots 6, 7, 8, 9 and 11 the gelatine block length was 125 mm which was cut for measurement into two sections of approximately 62.5 mm.

ized by dividing the velocity change $\Delta v = v_i - v_r$ with impact velocity (Figs. 6 and 7). The differences in bullet channel lengths were rather small and assumed not to introduce significant error.

The null-hypothesis of equal means could not be rejected for the 9 mm bullet at 95% level of significance as the z -score of -1.46 is clearly within the critical range of ± 1.96 . As for the 7.62×39 bullets Fig. 7 shows that the majority of decelerations by Berlin et al. [2] are precisely in line with gelatine tests. There are two observations with exceptionally

high decelerations probably caused by bullet tumbling. If those two observations are removed the z -score is 0.177 and clearly within the critical range. The decelerations obtained by Albreht et al. [9] are slightly higher in average than those of gelatine giving z -score of -5.25 . The data on velocity measurement technique and distances is somewhat insufficient in [9] to allow analysis of the cause.

The deceleration figures obtained therefore add evidence confirming the validity of 10% ballistic gelatine when used at the temperature of $+4^\circ\text{C}$.

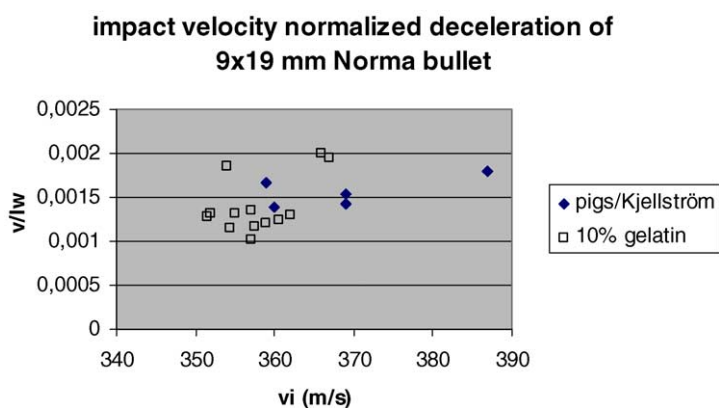


Fig. 6. Deceleration of 9 mm × 19 mm Norma Säkerhetspatron bullet normalized with impact velocity.

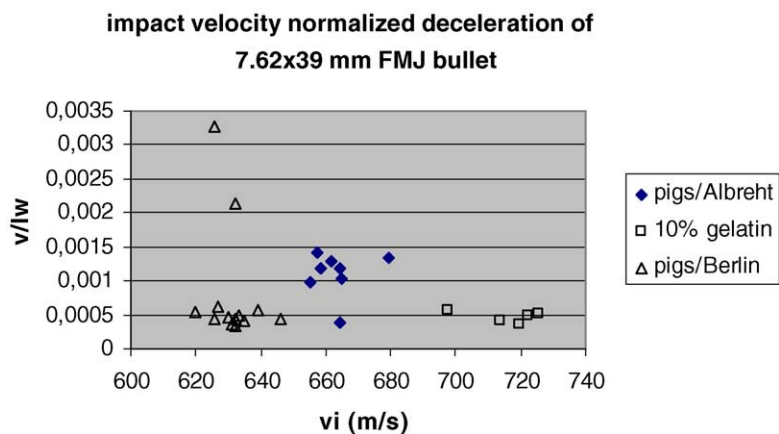
Fig. 7. Deceleration of 7.62 mm \times 39 mm bullet normalized with impact velocity.

Table 2

Calculated energy ratio RE

Shot no.	Method	$s(0-50)$	$s(50-100)$	$s(100-150)$	$s(150-200)$	$s(200-250)$	Total
Energy ratios RE for 9×19							
1	FSA	2779.5	5890.3	4264.0	4923.5	4546.3	22403.5
	TCLM	69437.4	145977.1	115752.1	87467.1	22920.5	441554.2
	WPM	19657.4	61650.7	66679.7	50986.0	18929.1	217902.8
2	FSA	2594.0	5991.3	2966.5	3148.8	5204.0	19904.5
	TCLM	60774.2	100806.8	51590.2	63396.9	29412.0	305980.1
	WPM	34762.2	63627.8	46830.7	46857.6	17446.5	209524.8
3	FSA	1852.3	4034.5	4964.8	4082.0	4967.0	19900.5
	TCLM	31971.2	104277.5	113361.9	82448.0	26979.0	359037.5
	WPM	28735.0	81579.4	79786.4	59931.8	21137.1	271169.6
4	FSA	2220.5	4300.0	4672.5	3869.0	5834.0	20896.0
	TCLM	45103.3	117726.0	106957.6	95304.8	36394.9	401486.5
	WPM	28397.3	66869.1	61996.0	53898.9	19386.9	230548.2
5	FSA	2255.5	4675.5	5854.5	3764.3	4331.8	20881.5
	TCLM	46471.2	139488.9	117696.2	65670.3	20980.0	390306.6
	WPM	23176.7	61236.0	57892.6	45188.7	16965.9	204459.9
6	FSA	4173.1	12019.4				16192.5
	TCLM	123845.4	117552.4				241397.8
	WPM	47129.8	43032.6				90162.4
7	FSA	3050.9	8652.8				11703.8
	TCLM	67572.2	62775.5				130347.7
	WPM	51813.1	47543.8				99356.9
8	FSA	3557.2	10171.6				13728.8
	TCLM	90841.2	85369.4				176210.6
	WPM	38944.9	35171.0				74115.9
9	FSA	2249.4	6248.1				8497.5
	TCLM	37848.3	34120.3				71968.6
	WPM	33381.2	29847.6				63228.8
14	FSA	2312.0	4557.5	4206.0	4722.5	4917.5	20715.5
	TCLM	48269.0	117229.3	112625.9	91787.9	26484.2	396396.3
	WPM	30349.4	87519.1	80538.0	49811.4	15288.6	263506.4

Table 2 (Continued)

Shot no.	Method	s(0–50)	s(50–100)	s(100–150)	s(150–200)	s(200–250)	Total
15	FSA	2635.3	6255.3	3312.0	4434.5	4287.5	20924.5
	TCLM	62156.7	99102.2	70625.2	74647.1	20590.5	327121.7
	WPM	26236.1	58455.7	61628.5	56742.4	17304.4	220367.3
16	FSA	1982.3	4084.5	3222.3	3400.0	5157.5	17846.5
	TCLM	35929.9	75749.6	66119.8	73606.8	28926.3	280332.4
	WPM	26317.3	76436.9	60509.8	39120.8	16835.1	219219.9
17	FSA	1770.0	3361.3	3591.3	4120.0	4677.5	17520.0
	TCLM	28964.0	71926.3	82197.8	77314.5	24150.7	284553.3
	WPM	22847.8	67857.8	75033.6	56875.4	18068.9	240683.4
Mean	FSA	2571.7	6172.5	4117.1	4051.6	4880.3	17778.1
	TCLM	57629.5	97853.9	92991.9	79071.5	26315.3	292822.6
	WPM	31672.9	60063.7	65655.0	51045.9	17929.2	184942.0
S.D.	FSA	663.1	2506.1	889.7	549.6	460.1	4022.2
	TCLM	25521.5	30215.1	23983.3	10461.2	4665.7	107965.6
	WPM	9130.2	16619.1	10439.7	6228.2	1604.0	71629.8
Energy ratios RE for 7.62×39							
11	FSA	5665.3	16266.3				21931.6
	TCLM	226093.3	241323.9				467417.2
	WPM	67350.3	76698.3				144048.5
12	FSA	3071.8	6243.0	5541.3	7691.3	14222.6	36769.9
	TCLM	83512.0	204411.2	195536.0	384941.2	242915.1	1111315.4
	WPM	29359.9	66721.5	84745.7	185723.1	122805.5	489355.8
13	FSA	2914.5	5642.3	5925.5	7227.5	6079.8	27789.5
	TCLM	75376.9	202201.1	223709.2	174932.0	53911.3	730130.6
	WPM	37865.9	113291.5	157448.0	163187.2	65263.7	537056.4
18	FSA	2502.0	6015.8	7635.0	6557.5	9922.8	32633.0
	TCLM	860.3	1914.9	2430.3	2087.3	3030.9	10323.7
	WPM	23511.2	80567.2	104521.4	124261.1	64091.6	396952.5
19	FSA	502134.5	1765035.2	3730464.7	3875488.3	947709.2	10820831.9
	TCLM	55628.7	178835.5	377975.1	392669.1	149336.8	1154445.1
	WPM	28310.9	98332.8	211106.3	253415.0	135261.0	726425.9
Mean	FSA	103257.6	359840.5	937391.6	974241.1	244483.6	2187991.2
	TCLM	88294.3	165737.3	199912.7	238657.4	112298.5	694726.4
	WPM	37279.6	87122.2	139455.3	181646.6	96855.5	458767.8
S.D.	FSA	199441.6	702608.7	1612581.7	1675035.9	406017.7	4316423.2
	TCLM	74686.0	84318.4	133501.8	162130.2	91898.0	425727.1
	WPM	15731.0	16603.2	49170.9	46907.3	32480.4	190564.9

4. Discussion

The fact that makes FSA and TCLM problematic is that all the cracks of a section must be measured. This introduces a source for error since it is not self evident what constitutes a crack or a fissure and how should its length be measured. Some of the fissures in Fig. 2 are clear, but how should the forked cracks and the pulped area in the middle be interpreted? Colouring the bullet channel with dye might add clarity.

The gelatine was cut for measurement into 50 mm sections. One can hypothesize that thinner sections of 10 or 25 mm would give different results. On the other hand the

above interpretation problem will certainly introduce multiplication of measurement error.

A reasonable size ammunition evaluation with sufficient number of test repetitions could easily raise the number of gelatine blocks and bullet channels to 150. The work required for measurement and analysis using the FSA and TCLM and thinner measurement sections will simply become prohibitive. The result of this experiment shows, however, that in this case measurement ease and accuracy go hand in hand. The WPM being the fastest and easiest method also seems to be the most accurate.

The length to diameter ratio of the 9×19 Norma bullet is approximately 3:2. When it tumbles the cross sectional area

Table 3
Bullet velocity and energy data

Shot no.	v_i (m/s)	v_{ic} (m/s)	m_i (g)	E_i (J)	v_r (m/s)	v_{rc} (m/s)	E_r (J)	E_d (J)	l_w (mm)	E_d/l_w
Velocity and energy data of 9×19										
1	357	355	8	504.10	238.00	238.46	227.45	276.65	250	1.11
2	359	357	8	509.80	236.00	236.03	222.84	286.96	250	1.15
3	364	362	8	524.18	245.00	245.08	240.25	283.93	250	1.14
4	359	357	8	509.80	266.00	266.17	283.38	226.41	250	0.91
5	354	352	8	495.62	236.00	236.07	222.91	272.71	250	1.09
6	369	367	8	538.76	278.00	278.21	309.61	229.14	125	1.83
7	368	366	8	535.82	272.00	274.11	300.55	235.28	125	1.88
8	361	359	8	515.52	305.00	305.19	372.57	142.95	125	1.14
9	356	354	8	501.26	272.00	272.24	296.47	204.80	125	1.64
14	360	357.5	8	511.23	253.00	253.04	256.11	255.12	250	1.02
15	357	354.5	8	502.68	253.00	253.00	256.04	246.65	250	0.99
16	363	360.5	8	519.84	248.00	248.10	246.21	273.64	250	1.09
17	354	351.5	8	494.21	240.00	240.00	230.40	263.81	250	1.06
Mean	360.08	357.92		512.52	257.08	257.36	266.52	246.00	211.54	1.23
S.D.	4.82	4.88		14.03	20.54	20.70	44.16	39.82	60.05	0.33
Velocity and energy data of 7.62×39										
11	716	713.5	8	2036.33	676.00	676.35	1829.82	206.51	125	1.65
12	722	719.5	8	2070.72	633.00	654.61	1714.06	356.66	250	1.43
13	725	722.5	8	2088.03	633.00	636.17	1618.83	469.19	250	1.88
18	700	697.5	8	1946.03	595.00	599.57	1437.95	508.07	250	2.03
19	728	725.5	8	2105.40	633.00	633.24	1603.99	501.41	250	2.01
Mean	718.20	715.70		2049.30	634.00	639.99	1640.93	408.37	225.00	1.80
S.D.	11.10	11.10		63.13	28.67	28.42	144.98	128.18	55.90	0.26
Reference	Pig wt.	Cal.	Bullet	m_i (g)	v_i (m/s)	E_i (J)	v_r (m/s)	E_d (J)	l_w (mm)	E_d/l_w
Results of pig tests (raw data)										
Albreht et al. [9]	58.78	7.62×39		8	679.3	1846.0	534.1	705.0	160	4.41
Albreht et al. [9]	64.42	7.62×39		8	658.6	1735.0	503.2	722.0	200	3.61
Albreht et al. [9]	62.04	7.62×39		8	664.5	1766.0	499.7	767.0	210	3.65
Albreht et al. [9]	63.19	7.62×39		8	655.4	1718.0	522.5	626.0	210	2.98
Albreht et al. [9]	62.38	7.62×39		8	664.8	1768.0	485.5	825.0	260	3.17
Albreht et al. [9]	62.54	7.62×39		8	664.5	1766.0	603.9	307.0	240	1.28
Albreht et al. [9]	60.64	7.62×39		8	661.4	1750.0	455.8	919.0	240	3.83
Albreht et al. [9]	61.54	7.62×39		8	657.5	1729.0	508.7	694.0	160	4.34
Berlin et al. [2]	67–93	7.62×39	Russian	8	626.0	1546.0	593.3	138.0	120	1.15
Berlin et al. [2]	67–93	7.62×39	Russian	8	631.0	1574.0	607.9	96.0	105	0.91
Berlin et al. [2]	67–93	7.62×39	Russian	8	633.0	1582.0	602.5	130.0	100	1.30
Berlin et al. [2]	67–93	7.62×39	Russian	8	626.0	1549.0	215.6	1363.0	200	6.82
Berlin et al. [2]	67–93	7.62×39	Russian	8	632.0	1579.0	595.2	162.0	130	1.25
Berlin et al. [2]	67–93	7.62×39	Russian	8	630.0	1567.0	593.3	159.0	123	1.29
Berlin et al. [2]	67–93	7.62×39	Russian	8	639.0	1614.0	610.5	123.0	78	1.58
Berlin et al. [2]	67–93	7.62×39	Russian	8	635.0	1595.0	606.2	125.0	109	1.15
Berlin et al. [2]	67–93	7.62×39	Russian	8	631.0	1576.0	595.2	159.0	153	1.04
Berlin et al. [2]	67–93	7.62×39	Russian	8	632.0	1578.0	603.3	122.0	135	0.90
Berlin et al. [2]	67–93	7.62×39	Russian	8	646.0	1648.0	615.2	134.0	108	1.24
Berlin et al. [2]	67–93	7.62×39	Russian	8	632.0	1577.0	361.6	1054.0	200	5.27
Berlin et al. [2]	67–93	7.62×39	Russian	8	627.0	1554.0	599.4	117.0	70	1.67
Berlin et al. [2]	67–93	7.62×39	Russian	8	620.0	1518.0	570.1	218.0	150	1.45
Mean		7.62×39			663.2	1759.8	514.2	695.6	210.0	3.4
S.D.		7.62×39			17.0	96.7	97.4	382.3	55.1	1.7
Kjellström et al. [8]	60	9×19	Norma SP	8	360.0	518.4	315.0	121.5	90	1.35
Kjellström et al. [8]	47	9×19	Norma SP	8	369.0	544.6	322.0	129.9	83	1.57

Table 3 (Continued)

Reference	Pig wt.	Cal.	Bullet	m_i (g)	v_i (m/s)	E_i (J)	v_r (m/s)	E_d (J)	l_w (mm)	E_d/l_w
Kjellström et al. [8]	42	9 × 19	Norma SP	8	369.0	544.6	332.0	103.7	70	1.48
Kjellström et al. [8]	53	9 × 19	Norma SP	8	359.0	515.5	320.0	105.9	65	1.63
Kjellström et al. [8]	60	9 × 19	Norma SP	8	387.0	599.1	324.0	179.2	91	1.97
Mean		9 × 19			368.8	544.5	322.6	128.1	79.8	1.6
S.D.		9 × 19			11.2	33.5	6.2	30.6	11.8	0.2

Table 4

RE correlation with measured E_d

RE correlations with measured E_d			
Method	9 × 19	7.62 × 39	All
FSA	0.63	0.45	0.51
TCLM	0.61	0.14	0.49
WPM	0.76	0.82	0.89

does not vary as much as with the 7.62 mm bullet having a ratio of approximately 3:1. The latter causes significant amount of dispersion in deceleration measurements and would thus require many more observations to give reliable validation data than the short 9 mm Norma bullet.

The number of pig tests done with the 9 mm Norma bullet was only 5. It is therefore, not sensible to present the results as conclusive evidence of the fidelity of 10% gelatine at the usage temperature of +4 °C. The results, however, add to the earlier evidence presented in literature [1,11,12]. The results show that the shroud does not have any detrimental effects on the measurement of E_d , rather on the contrary.

Without the shroud the longest fissures tend to be directed towards the bottom and the supporting platform. The shroud seems to suppress the boundary interaction with the platform causing the fissures to be more evenly distributed in all radial directions especially when high E_d ammunition are used. One can, however, debate the importance of symmetric expansion of the simulant as long as the fissures do not break the surface letting the pressure escape. If all the pressure is held inside the wound cavity the E_d is reflected by the fissures even if they are not symmetrically distributed.

Increasing the size of the simulant block will also reduce the effect of asymmetric expansion. It will also make the blocks heavy and cumbersome to handle. The bigger the block the more it will cost and the more storage space it will take. Further testing has shown that a gelatine block of 20 cm × 20 cm × 25 cm with the shroud can easily handle one SS109 or expanding high E_d bullet of calibre 5.56 × 45 or four shots of expanding 9 mm × 19 mm bullets. An expanding 7.62 × 51 bullet will, however, still make the fissures reach the surface and requires the use of an even larger block if E_d distribution along the wound channel needs to be measured. Even when the block surface is ruptured the total E_d can be measured using Eq. (1) as the pressure escape occurring after the passage of the bullet does not have any effect on the penetration resistance offered by the simulant to

the bullet. Also the depth of maximum kinetic energy release can be estimated.

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References

- [1] K.G. Sellier, B.P. Kneubuehl, *Wound Ballistics and The Scientific Background*, Elsevier, 1994 ISBN 0-444-81511-2.
- [2] R.H. Berlin, B. Janzon, B. Rybeck, J. Sandegård, T. Seeman, Local effects of assault rifle bullets in live tissues. Part II. Further studies in live tissues and relations to some simulant media, *Acta Chir. Scand. Suppl.* 477 (1977) 1–48.
- [3] B. Janzon, B. Schantz, T. Seeman, Scale effects in ballistic wounding, *J. Trauma* 28 (Suppl. 1) S29–S32.
- [4] F. Tian-Shun, M. Yuyuan, F. Rong-Xiang, L. Ming, The wounding characteristics of spherical steel fragments in live tissues, *J. Trauma* 28 (Suppl. 1) (1988) S37–S40.
- [5] B.D. Ragsdale, A. Josselson, Predicting temporary cavity size from radial fissure measurements in ordnance gelatin, *J. Trauma* 28 (Suppl. 1) (1988) S5–S9.
- [6] M.L. Fackler, J.A. Malinowski, The wound profile: a visual method for quantifying gunshot wound components, *J. Trauma* 25 (6) (1985) 522–529.
- [7] J. Jussila, Preparing Ballistic Gelatine—Review and Proposal for a Standard Method, *Forensic Sci. Int.* 141 (2004) 91–98.
- [8] B.T. Kjellström, J. Bursell, M. Skoglund, Sårballistisk utvärdering av polisiär tjänsteamunition; FOI Memo FOI 2002-1625; Totalförsvarets Forskningsinstitut, Stockholm, August 2002 (Swedish)
- [9] M. Albrecht, D. Scepanovic, A. Ceramilac, V. Milivojevic, S. Berger, G. Tasic, V. Tatic, M. Todoric, D.j. Popovic, N. Nanushevic, Experimental soft tissue wounds caused by standard military rifles., *Acta Chir. Scand.* 489 (Suppl.) (1979) 185–198.
- [10] B. Janzon, T. Seeman, Muscle devitalization in high-energy missile wounds and its dependence on energy transfer, *J. Trauma* 25 (2) (1995) 138–144.
- [11] M.L. Fackler, Muscle devitalization in high-energy missile wounds and its dependence on energy transfer, Letter to Editor, *J. Trauma* 26 (3) (1986) 297.
- [12] N. Yoganandan, F.A. Pintar, S. Kumaresan, D.J. Maiman, S.W. Hargarten, Dynamic analysis of penetrating trauma, *J. Trauma* 42 (2) (1997) 266–271.